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Developing summary measures of health-related multiple physical environmental deprivation for epidemiological research

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ABSTRACT

Socioeconomic deprivation accounts for much of the spatial inequality in health in the UK, but a significant proportion remains unexplained. It is highly likely that the physical environment is a key factor in this unexplained variation. The role of the socioeconomic environment in health inequalities has been studied using small-area measures of multiple socioeconomic deprivation that capture the burden of socioeconomic adversity. Although similar composite measures of the physical environment would greatly assist investigations of environmental determinants of health no such measures are available. In this study we developed two small-area measures of health-related multiple physical environmental deprivation for the UK. A thorough review and evidence appraisal process was used to identify health-relevant dimensions of physical environmental deprivation. As a result we selected both health-detrimental (air pollution, cold climate, industrial facilities) and health-beneficial (ultraviolet radiation and green space) dimensions. Data sets describing each of the selected dimensions were acquired, and rendered to UK Census Area Statistics wards (n = 10,654, average population = 5,518). We developed two summary measures: an index (MEDIx) and a classification (MEDClass). MEDIx, on an ordinal scale, can be used to distinguish areas exposed to greater or lesser environmental deprivation. MEDClass groups areas with similar environmental characteristics and will be useful for exploring health effects of specific types of environment. Mapping these measures demonstrated a wide variation in physical environmental deprivation across the UK. MEDIx revealed greater environmental deprivation in urban and industrial areas, and at more northerly latitudes. Although created using a different methodology MEDClass also differentiated these environmental types. We concluded that it is possible to capture and characterise multiple attributes of health-related physical environmental deprivation in the UK, at a small area level. The measures we developed offer opportunities to researchers and policy makers for developing our understanding of the role of exposure to multiple dimensions of physical environmental deprivation on health outcomes.

KEYWORDS

Physical environment, socioeconomic deprivation, health, UK, epidemiology

INTRODUCTION

In the UK spatial inequalities in health have long been identified, and there is clear evidence that these geographical differences continue to widen (Shaw et al., 2005). Whilst the geographical distribution of socioeconomic deprivation explains much of the spatial inequality in health in the UK, (with greater socioeconomic deprivation in an area almost always associated with worse population health) a significant proportion remains unexplained (Mitchell et al., 2000). It is likely that the physical environment also has an important role in health inequalities (Marmot, 2001). Furthering our understanding of the pathways that link the characteristics of areas to individual-level health outcomes offers significant potential to deliver sustainable policy options for improving the health of residents in the most disadvantaged places. Ameliorating health inequalities is a political and moral priority (Woodward and Kawachi, 2000).

Composite measures of socioeconomic deprivation (e.g., the Carstairs index, Carstairs and Morris, 1989; and the Townsend index, Townsend et al., 1987) are widely used in epidemiological research, and have greatly facilitated research into the relationships between area-level socioeconomic deprivation and poor health. These measures reflect that the socioeconomic environment is multidimensional (e.g., income, employment, living conditions and social class) and that socioeconomic disadvantage tends therefore to be inadequately measured by any one dimension. They typically describe the relative level of socioeconomic deprivation in an area based on the degree of various social and material indicators including, for example, small area Census data on unemployment, housing tenure or car ownership. The purpose of the measures is *not* to aid in exploring the role of the constituent characteristics in the aetiology of disease; rather it is to identify populations with relatively higher or lower 'burden' of adversity. Such measures can effectively simplify visualisation, analysis and understanding of a multidimensional phenomenon (Nardo et al., 2008). In providing a broader context a summary measure can be easier to interpret than its individual component variables, and hence can be a valuable tool for decision makers (Corvalán et al., 2000a; Saisana and Tarantola, 2002).

The physical environment is similarly multidimensional: including exposures that may be either pathogenic (e.g., air pollution, contaminated water) or salutogenic (literally health creating, such as moderate exposure to sunlight). Populations may experience 'multiple exposures to a plethora of suboptimal environmental conditions' (p.304; Evans and Kantrowitz, 2002), and these exposures may have a simultaneous (and potentially multiplicative) influence on health. However, rather than trying to capture the multidimensional nature of the physical environment, previous epidemiological studies have tended to focus on specific components of the physical environment in isolation (e.g., air pollution: Finkelstein et al., 2005). Developing methods to quantify area-level health-relevant multiple environmental deprivation would assist in advancing our knowledge of the environmental determinants of health.

Although a range of environmental summary measures have been developed elsewhere, none have sought to summarise multiple environmental deprivation in a comprehensive and specifically health-relevant way. The English Indices of Multiple Deprivation have included a Living Environment domain since 2004 (Noble et al., 2008; Office of the Deputy Prime Minister, 2004) which summarises the quality of indoor (heating and housing condition) and outdoor (air pollution and road traffic accidents) environments, although the basis for selecting these factors, and excluding others, is not clear. Wheeler (2004) created separate summary measures for two environmental dimensions selected for their health-relevance (air quality and industrial emissions) but did not address the physical environment as a whole. Elsewhere, environmental indices have been produced for applications other than health research, such as land-use planning (Pruppers et al., 1998; Sol et al., 1995).

Although summary measures, or 'composite indicators', are proving increasingly popular with policy-makers, their development and use has been criticised. Whilst a composite measure provides a usable and easily understandable snapshot of a complex multivariate phenomenon, there is concern that trends in the underlying data may be over-simplified and distorted (Briggs, 2000). Thus, poorly constructed summary measures may invite simplistic or misguided policy conclusions (Saisana and Tarantola, 2002). However, the advantages of composite measures of socioeconomic deprivation for identifying relatively more and less advantaged populations have been amply demonstrated by epidemiologists. Similarly, a composite measure of physical environmental deprivation would offer considerable potential for improving our understanding of the importance of physical contexts as determinants of health.

In this paper we develop a clearly justified and carefully constructed health-based summary measure of multiple environmental deprivation at the UK small area level, akin to the aforementioned measures of multiple socioeconomic deprivation. We detail our approach, the results of which were two complementary summary measures of multiple physical environmental deprivation. Developing the measures was an exploratory process which asked 'can it be done?' as much as 'how do we do it?'. In our ongoing work we will investigate the utility of these measures in epidemiological analyses. In particular, we will evaluate the influence of multiple environmental deprivation on a variety of health outcomes.

MATERIALS AND METHODS

We developed our UK measure of multiple environmental deprivation in four stages: 1) identifying environmental dimensions with health relevance for the UK, 2) acquiring and processing data to describe the selected dimensions of the environment, 3) checking associations between selected dimensions and health in the UK, and 4) constructing the summary measures.

Stage 1: Identifying health-relevant dimensions of environment

We first defined the physical environment as consisting of external physical, chemical and biological dimensions, and excluding social and cultural dimensions. In this paper the term 'environment' is used as a shorthand for the physical environment, as per this definition. A scoping review of literature identified a 'long list' of environmental dimensions with the potential for health impacts for the UK population:

- Air pollutants
- Climate
- Solar ultraviolet (UV) radiation
- Green space
- Industrial pollution
- Drinking water quality
- Noise pollution
- Extremely low frequency radiation (power lines)
- Radio frequency radiation (radio and TV transmitters)
- Radon
- Nuclear facilities
- Contaminated land

We systematically searched publication databases (e.g., PubMed and ISI Web of Knowledge) for empirical evidence of the health impacts of the environmental dimensions listed above, in order to justify their inclusion or exclusion. The assembled evidence was then appraised based on prevalence of the health outcome(s), rigour of the study design, and the strength of association established (further detail of this process is provided in Richardson et al., 2009, in press).

We selected only environmental dimensions for which clear associations with health had been established, to which at least 10% of the UK population were exposed, and for which reliable and representative UK-wide data were available. This appraisal resulted in selection of five environmental dimensions with public health relevance for the UK. Below we briefly outline some key epidemiological evidence for the health associations of each environmental dimension we selected, although the full evidence review for each was more comprehensive than can be reported here.

Exposure to outdoor ambient air pollutants: Elevated risks of respiratory disease (RD), cardiovascular disease (CVD) and total mortality are consistently associated with air pollutants (especially PM_{10}), at concentrations frequently experienced in urban settings (Bell et al., 2005; Ito et al., 2005; Levy et al., 2000; Schwartz, 1994; Stieb et al., 2002; World Health Organization, 2004). Evidence of health effects are strongest for particulate matter (PM_{10}) and ozone (O_3), but also substantial for carbon monoxide (CO), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2).

Ambient climate (hot and cold temperatures): Increased risks of CVD, RD and total mortality with both elevated and reduced temperatures were found in many studies (Basu and Samet, 2002; Curriero et al., 2002; Martens, 1998). Small but persistent elevations in risk are seen with each incremental deviation away from the UK's comfort temperature of approximately 20°C (Martens, 1998), hence the entire population are exposed.

Solar UV radiation: UV radiation is the main risk factor for skin cancer (Elwood and Jopson, 1997; Reichrath, 2006), but a consistent protective effect of UV (via vitamin D production) has been found against a number of more prevalent cancers (Krause et al., 2006; Reichrath, 2006; van der Rhee et al., 2006). All studies on prostate, breast and ovarian cancer that were systematically reviewed by van der Rhee et al. (2006)

showed a significant inverse relationship between sunlight and incidence or mortality. Most of the UK population experience some vitamin D deficiency in winter because of inadequate exposure to solar UV (Gillie, 2004).

Proximity to industrial facilities: There is evidence that residence within approximately 4 km of waste management sites (Floret et al., 2003; Goldberg et al., 1995) or within approximately 1.6 km of metal production/processing plants (Brown et al., 1984; Tollestrup et al., 2003) increases some cancer risks. Evidence of health effects was inconsistent for refineries and combustion installations, and weak or non-existent for other facilities, hence we included only waste management and metal production/processing sites. Analysis using a geographical information system (GIS) revealed that 21% of the UK population resided within the relevant effect buffers reported for these sites.

Access to green space: There is evidence that more natural environments have a beneficial effect on people's self-perceived health, blood pressure, levels of overweight and obesity and total mortality risks (de Vries et al., 2003; Ellaway et al., 2005; Hartig et al., 2003; Maas et al., 2006; Mitchell and Popham, 2007, 2008; Sugiyama et al., 2008; Takano et al., 2002). Population exposure to green space varies markedly across the UK and there is no indication of a minimum threshold for health.

Stage 2: Dataset acquisition and processing

We selected UK 2001 Census Area Statistics (CAS) wards as our geographical unit of analysis. Wards were considered suitably geographically-specific to be sensitive to the finer scale environmental variations (e.g., air pollution) but also sufficiently large to provide adequate populations for ecological analyses for which the summary measures might be used. Census geographies are widely used because of their compatibility with published statistics (such as mortality records), their contiguity with administrative boundaries, and their availability for the whole UK. There were 10,654 CAS wards in the UK at the 2001 Census, with a mean population of 5,518.

Datasets capturing the environmental dimensions were carefully selected in order to ensure scientific validity and maximise future utility and reproducibility of the summary measures (Nardo et al., 2008; Sol et al., 1995). For each environmental dimension we sought and obtained data that were spatially contiguous, comprehensive across the UK and centred around 2001 (Table 1). 2001 was selected to correspond with the decennial Census which would be our source of denominator data for subsequent testing of the utility of the summary measures. For ambient environmental factors that were typically monitored at discrete locations (climate and air pollutants) we achieved UK-wide contiguity by using gridded datasets from validated models. Using the geographical information system software ArcMap (ESRI, Redlands, CA) we rendered each environmental dataset to 2001 CAS wards.

Where feasible we calculated population-weighted average exposure to the environmental dimensions for each ward, in order to represent the environmental conditions experienced where the population were most heavily concentrated. The wards consisted of a number of smaller Census output areas (OAs) for which centroids and population counts were available. Therefore, for air pollution, UV radiation and climate, we calculated population-weighted average exposure for each ward from the values of each dimension at the centroid of each constituent OA, weighted by the OA's population. The OAs within 1.6 km of a metal processing plant or 4 km of a waste management site were identified in ArcMap, and used to calculate the proportion of each ward's population living in 'health-relevant' proximity to each type of industrial facility. Percentage green space per ward was predicted using a regression model developed from two green space datasets (the Generalised Land Use Database (Office of the Deputy Prime Minister, 2001) and the Coordination of Information on the Environment (CORINE) land cover dataset (EEA, 2000)). This process is described in greater detail in a forthcoming publication (Richardson and Mitchell, in review).

Stage 3: Associations between selected dimensions and health

As our literature search had included high quality evidence from countries outside the UK we needed to ensure that each environmental dimension had UK health-relevance. A preliminary analysis was conducted to confirm that each of the derived environmental dimensions had the expected associations with a selection of health outcomes. The health outcomes were chosen because they had a biologically plausible and established link to the corresponding environmental characteristic (e.g., air pollution with mortality from respiratory disease). Adjustment was made for the age, sex and socioeconomic deprivation profiles of each area.

Socioeconomic deprivation, health outcome and population data were required at the same spatial scale as the environmental data. We selected the Carstairs score (Carstairs and Morris, 1989) as our measure of socioeconomic deprivation. The score has been widely used in health-related research, and can be derived for the whole of the UK using Census data. Other measures of socioeconomic deprivation (e.g., the various national indices of multiple deprivation) were either not available for the whole UK or for 2001 CAS wards. We calculated UK-wide Carstairs scores for 2001 CAS wards using standard methodology.

Individual-level mortality records (including age, sex, cause of death and area of residence at death) were obtained from the Office for National Statistics (ONS) for England and Wales, the General Register Office for Scotland (GROS) and the Northern Ireland Statistics and Research Agency (NISRA), and matched to 2001 CAS wards. The records covered a five-year period centred on the 2001 Census (1999 to 2003), except for in Scotland where pre-2001 georeferencing issues made the use of 2001 to 2005 data more appropriate. Counts of all-cause and cause-specific mortality (e.g., cardiovascular disease, respiratory disease, all cancer, lung cancer) were generated by sex, age-group (0-15, 16-34, 35-49, 50-59, 60-64, 65-84, 85+) and ward. Two ward-level measures of self-reported morbidity from the 2001 Census were also obtained, capturing population reporting that their general health in the preceding 12 months was 'not good', and those reporting having a 'limiting long term illness'. Ward-level age-group and sex-specific population estimates were obtained for 2001 from ONS and NISRA, and for 2003 for Scottish wards from GROS. This provided a total study population of 58.8 million, with 2.9 million deaths across the 5 year period.

Due to over-dispersion of the health outcome data (i.e., the variance for each health outcome exceeding its mean), Poisson regression was unsuitable (Hilbe, 2007). Instead, negative binomial regression modelling was used, as an additional parameter in the negative binomial distribution is used to account for data with large variance (Hilbe, 2007). Analyses were conducted in Stata 10 (StataCorp, College Station, TX). Models were adjusted for age-group, sex and Carstairs deprivation quintile. For each environmental variable identified as a risk factor in the literature, we confirmed the expected relationships with the relevant health outcomes. This step also helped us to determine how to treat dimensions that lacked approximately linear associations with health: temperature (having detrimental health effects at both extremes of exposure) and UV radiation (with increased exposure linked to both detrimental and beneficial effects). The analysis showed that, for the ranges of these dimensions experienced in the UK, colder temperatures and lower UV levels have greater detrimental consequences for population health than their opposite extremes.

Stage 4: Construction of the summary measures

We then considered how to combine the data into summary measures of multiple environmental deprivation. We decided to develop both an index and a classification. The index would use an ordinal scale to distinguish areas exposed to greater or lesser environmental deprivation: a useful attribute for dose-response epidemiological analyses, and for the dissemination of results to a non-technical audience. Alternatively, the classification would group areas with similar environmental characteristics. This approach would be useful for exploring health effects of specific combinations of environments but would not permit quantitative ranking. The groupings produced would simply represent environments that were different, with no explicit indication of which combinations were better or worse for health.

Stage 4a: Index

Indices are often calculated by combining the standardised scores of relevant variables, or 'subindicators' (e.g., Carstairs and Morris, 1989; United Nations, 2001). However, in the current study this approach was unsuitable because it would prevent determination of whether an area with a high multiple environmental deprivation score was subject to modest exposure across the whole range of pathogenic environmental dimensions, or severe exposure to just one or two dimensions. Subindicators are also often weighted to reflect the relative importance of each to the multivariate concept (Saisana et al., 2005). We decided against weighting our environmental dimensions because of the absence of evidence with which to quantify their relative health risks. Any weighting factors would therefore have been arbitrary. Furthermore, the health impact of each environmental dimension will vary according to the health outcome. Different weighting schemes would therefore needed to have been developed for each health outcome of interest.

Our approach recognised the evidence that some of our environmental dimensions are largely detrimental to health (air pollution, cold climate, and proximity to industrial facilities) while other dimensions are principally beneficial (UV radiation and green space). Our index reflected the number of environmental dimensions each ward was exposed to at ‘detrimental’ or ‘beneficial’ levels. Ideally the threshold levels for ‘detrimental’ and ‘beneficial’ would have been determined from the literature. However, our review revealed no clear, consistent threshold of harm or benefit for any of our selected dimensions. Even air pollution, which is subject to internationally agreed quality standards, has been shown to have harmful effects at levels below these thresholds (Barnett et al., 2006).

In the absence of clear guidance, we defined these ‘health-relevant’ levels based on the distribution of values for each dimension across the UK by rendering the wards into exposure quintiles. For each environmental dimension, wards in the highest exposure quintile were then given a score of +1 for pathogenic/detrimental dimensions, or -1 for salutogenic/beneficial dimensions. Detrimental air pollution was defined as the upper quintile of any of the traffic/industry-related air pollutants (PM_{10}, NO_2, SO_2 or CO). Ozone (O_3) was excluded from the index because it was inversely correlated with the other pollutants and confounded interpretation of this dimension. To maintain ease of interpretation of the index we selected a single climate measure, average temperature, as this gave the strongest and most consistent associations with health. Summing the scores within each ward gave a Multiple Environmental Deprivation Index (MEDIx) score (for an example calculation see Table 2). MEDIx scores ranged from -2 to +3, with a score of +3 denoting the most 'environmentally deprived' areas.

Stage 4b: Classification

With regards to developing the environmental classification, we sought to classify wards based on their exposure to the environmental dimensions, such that all wards exposed to a specific combination would be grouped together. Our approach bears resemblance to geodemographic profiling techniques (Harris et al., 2005), but classifies areas based on their environmental characteristics rather than the attributes of their population.

To prevent air pollution and climate dominating the classification (by virtue of the number of indicators relating to these factors) we used Principal Components Analysis (PCA) to reduce each of these dimensions into a single component that accounted for most of the variance in the original variables. The PCA conducted for the air pollutants produced a single component that accounted for 70% of the variance in the original variables. The PCA conducted for the climate variables also included UV, to remove the latitudinal gradient in these correlated variables which would have biased the resulting classification. This approach produced a component that accounted for 53% of the variance in the original data. Wards were therefore classified on the basis of four variables: the air pollution PCA component, the climate and UV PCA component, proximity to industrial facilities and green space availability.

After careful consideration of a variety of clustering methodologies a two-step clustering procedure (in SPSS software, SPSS Inc., Chicago, IL) was selected for our study. Two step clustering procedures use hierarchical methods and were chosen due to their suitability for large datasets. We repeated the clustering procedure a number of times to assess the degree of random variation in the solutions produced, and found extremely close agreement in cluster membership between the duplicate solutions.

A range of solutions with different numbers of clusters was produced. The results were evaluated to identify the number of clusters that would capture the salient environmental differences most effectively and efficiently. We wanted to identify clusters which were both environmentally meaningful but which also contained a sufficiently large population for future epidemiological analyses. We thus weighed the benefits of increased within-group homogeneity against the costs of increasing complexity of the classification (i.e., number of clusters) (Bryan, 2006) using a variation of the elbow criterion. The elbow criterion is commonly used to select the optimal cluster solution, by graphing the solutions and identifying the ‘elbow’ point at which increased solution complexity is not compensated for by an adequate improvement in information conveyed by the solution (e.g., Domroes et al., 1998). For the groupings in each cluster solution we calculated standardised mortality and incidence rates (SMRs and SIRs) of our selected health outcomes, and plotted the mean range of these rates against the solution’s number of clusters (Figure 1). This approach allowed us to identify the solution that most adequately balanced the trade-off between maximising information conveyed (here: relevance in terms of health outcomes) and minimising complexity. We identified the seven-cluster solution as the elbow point, as this solution gave substantially better discrimination between health relevant types of environment (as demonstrated by a wide range in SIRs and SMRs) than the six-cluster solution. However, this gain in terms of health relevance tailed off with increasing solution complexity (eight or more clusters). Another criterion applied when selecting the most appropriate cluster solution was ease of naming: each cluster should be sufficiently different from the others (based on the environments that they typify) that it could be labelled in a clear and meaningful way. Otherwise the solution was deemed to be capturing too coarse or too fine a level of detail. The seven-cluster solution also met this criterion. This solution was labelled the Multiple Environmental Deprivation Classification (MEDClass).

RESULTS

Greater levels of physical environmental deprivation, as measured by the MEDIx score, were revealed in urban and industrial areas of the UK (Figure 2). A broad north-south gradient was also observed, with levels of physical environmental deprivation generally rising with increasing latitude. This observation is likely to reflect the inclusion of cold climate as a pathogenic component of environment and higher UV as a salutogen. Both of these dimensions are strongly related to latitude. The ‘strip’ of lowest environmental deprivation (in terms of health) across southern England is also strongly driven by climate and UV.

Incidences of the two extreme scores of MEDIx (-2 and +3) were uncommon (Table 3). These scores were only assigned to wards experiencing all of the beneficial environments and none of the detrimental environments, or *vice versa*. Table 3 also shows how the mean values for each environmental dimension vary by MEDIx score. Although the MEDIx score was based on counting the number of environmental dimensions for which a ward was in the highest quintile, rather than on the absolute values of the environmental dimensions themselves, increasing MEDIx score did tend to be accompanied by an increase in average exposure to detrimental dimensions and a decrease in average exposure to beneficial dimensions (Table 3).

MEDClass grouped wards into seven distinct environmental types which have been assigned labels to assist in identifying the combinations of environments they represent (Figure 3). Again, a clear distinction was apparent between the environments of northern and southern areas of the UK, furthermore this was also noted between urban and rural areas and, arguably, between different cities (something which MEDIx did not achieve). Once again the clear distinction between the rural south and rural areas of northern UK and upland Wales (clusters 7 and 6, respectively) is likely a function of UV and climate exposure.

Table 4 reveals the extent to which environments differed between clusters. Wards in cluster 1, for example, were exposed to significantly higher PM_{10}, NO_2 and CO concentrations, UV levels, numbers of cooling degree-days and longer duration of summer heatwaves than those in other clusters, and also were exposed to significantly less green space. This cluster was named ‘London and London-esque’ because 69% of its wards were within Greater London (with a population of 6.3 million, or 76% of the cluster’s population), and the remaining wards were from similar city-centre settings. It should be noted that as our objective was to characterise places based on their environmental characteristics rather than attributes of the people residing in the area, this finding does not denote homogeneity of the population within this, or indeed any, cluster. Rather, this observation indicates relative homogeneity in the type of physical environment characterising wards in the cluster, compared with those in other clusters.

Despite the different methodologies that were adopted to produce the two measures some broad similarities were apparent in how MEDIx and MEDClass characterised the physical environment in the UK (Figs 2 and 3, Table 5). The majority (70%) of the least environmentally deprived wards (MEDIx scores -2 and -1), were classified as cluster 7 ‘Sunny, Clean and Green’. Over 40% of the most environmentally deprived wards (MEDIx +2 and +3) were classified as cluster 2 ‘Industrial’. The distribution of wards between the MEDIx scores and MEDClass clusters deviated significantly from what might be expected if the two measures were not related (χ^2 = 6571, p < 0.001). However, figures 2 and 3 confirm that the two measures are sensitive to multiple environmental deprivation in different ways, reflecting the separate methodologies used to create each.

DISCUSSION

This study has argued that there is a pressing need to develop composite measures of multiple environmental deprivation to aid researchers in better understanding the pathways through which the physical environment can shape health outcomes and health-related behaviours. Such measures can be considered akin to the multitude of area-level measures of the socio-economic environment that are available in many countries and have enriched our understanding of geographical inequalities in health.

This UK research has provided two related methodologies for measuring health-related multiple environmental deprivation for Census wards across the country. We identified dimensions of physical environmental deprivation that are pertinent to health in a UK context, obtained suitable datasets and developed two complementary ward-level summary measures: MEDIx and MEDClass. The measures we developed offer considerable opportunities for research aimed at increasing our understanding of the role of exposure to multiple dimensions of physical environmental deprivation on health outcomes and health inequalities. MEDIx provides a scale measure of health-related environmental deprivation from the "best" to "worst" environments, and hence has utility for identification of areas that suffer from high levels of multiple environmental deprivation. MEDClass groups wards with similar environmental 'profiles', permitting the health influences of particular combinations of environmental characteristics to be studied. Our environmental measures should also be of considerable interest to policy makers. The tools we have developed could assist in the effective targeting of various interventions for the mitigation of environmental deprivation, which may ultimately improve health outcomes.

It is important to acknowledge the key limitations of our approach. First, the accuracy of our summary measures will be contingent on the quality of the data sets we have utilised. With this in mind we sought the most reliable data available, but we acknowledge that inaccuracies may exist in these datasets. We were also unable to obtain reliable and/or contiguous data sets for two key environmental dimensions that we identified at the outset: drinking water quality (specifically disinfection by-products), and noise pollution. These dimensions could be included in future attempts at summarising multiple environmental deprivation should suitable data become available. We anticipated that a useful composite indicator could be constructed using the remaining five dimensions.

Second, in creating MEDIx, our selection of the highest exposure quintile to identify wards with health-relevant exposure to each environmental dimension was clearly arbitrary. Using an alternative threshold may have produced different results, but we identified no robust evidence for health-relevant exposure thresholds. Nonetheless, defining this arbitrary threshold enabled us to identify the wards exposed to the most pathogenic/salutogenic environments in a simple and readily explainable way.

Third, our choice of spatial unit was based at least partly on the convenience of a unit for which Census and health outcome data were readily available. Rendering each environmental data set to this scale may have introduced error and also raises the possibility of the modifiable areal unit problem (MAUP) for those variables in which the true spatial scale of variation is smaller than ward level. However, the use of population-weighted centroids in the rendering process will have ensured that the most population-relevant values of each environmental exposure were assigned to each ward. Further, it is feasible that the *approach* we adopted to creating the summary measures could be applied at a variety of spatial scales.

Finally, there are limitations that are pertinent to the application of our environmental measures in epidemiological analyses. For instance, both MEDIx and MEDClass are cross-sectional measures for a single point in time and hence in our subsequent epidemiological investigations it will not be possible to ascertain a causal relationship between multiple environmental deprivation and health. Health-selective migration (Norman et al., 2005) might also play a role in any health differential found between areas of greater or lesser environmental deprivation. As migrants tend to be healthier than non-migrants and tend to move to less deprived areas (Norman et al., 2005) any health inequalities found may not be directly attributable to the physical environment. Future work could usefully develop environmental measures for different points in time and append these indices to longitudinal health data to determine causality and evaluate the impact of selective migration

Despite these constraints our approach has been underpinned by recognised principles from the literature, which has strengthened the work. Corvalán et al. (2000b) argue that any such summary measure should be demonstrably health relevant and target issues of real environmental health concern. By appraising the literature critically, including only those environmental dimensions with strong associations with health, by first testing each dimension individually for association with health, and by focusing on environmental dimensions to which at least 10% of the UK population is exposed we have ensured MEDIx and MEDClass are health-relevant in the UK context. Nardo et al. (2008) argue that the data sets included should be representative of the environmental factors of concern and of an acceptable quality. We identified and selected contiguous, UK-wide datasets from sources that had used well-documented methodologies. Where possible, the datasets were averaged over the study period (air pollutants, climate, UV index) although for green space and industrial facilities the use of 'snapshot' data was unavoidable. It is also advisable that these kinds of measures should use datasets that are readily available and routinely updated (Sol et al., 1995). As far as possible, we used readily available UK-wide datasets that are downloadable free-of-charge from the internet. The climate, UV, air pollution and industrial facilities data were extracted from monitoring databases that will be routinely updated. Green space data were derived using our own methodology, but based upon the freely available CORINE data (EEA, 2000; Sol et al., 1995).

Corvalán et al. (2000b) also advise that the measure should be largely unaffected by minor changes in methodology or scale. Although we used two different methodologies in order to produce complementary summary measures, the resulting spatial patterning of the indices showed some similarities, and both measures successfully captured health-relevant groupings. Further, the measure should be consistent and comparable over time and space, and easy for users to understand and apply (Corvalán et al., 2000b). We matched the temporal resolution of our environmental and health datasets where possible, and rendered each to a consistent geography for the whole UK. In terms of ease of use, both of our final products, MEDIx and MEDClass, have been developed in as transparent a way as possible, with all decisions clearly documented. Both are simple to map, query, and decompose to raw data.

CONCLUSIONS

In the absence of a method for quantifying multiple physical environmental deprivation for use in epidemiological research we developed two measures for this purpose: MEDIx and MEDClass. MEDIx, an index on an ordinal scale, can be used to distiguish areas exposed to greater or lesser environmental deprivation. Alternatively MEDClass, the environmental classification groups areas with similar environmental profiles, and hence can be used for exploring the health effects of specific combinations of environmental factors. The development of these measures recognised the multidimensional nature of the physical environment and its potential influences on health. We conclude that it is possible to capture and characterise multiple attributes of health-related physical environmental deprivation in the UK, at a small area level. MEDIx and MEDClass offer considerable potential for investigations of environmental determinants on health because they reflect the overall burden of adversity a population faces. Our index should also be of interest to researchers working in the fields of environmental disparities, environmental (in)justice and political ecology. However, key applications of the measures are likely to include investigations into environmental determinants of health outcomes, health behaviours and health inequalities. In particular MEDIx and MEDClass will, in combination with individual-level health data, assist in establishing the extent to which living in an area with relatively higher or lower levels of multiple environmental deprivation is a risk factor for adverse (or positive) health outcomes. This novel approach is likely to provide new insights into the environmental drivers of the widening disparities in health outcomes observed in the UK.

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TABLES

Table 1. A summary of the datasets acquired to derive a ward-level measure of each environmental dimension.

Dimension	Sub-dimensions	Data source
Air pollution	Particulate matter (PM_{10}) Ozone (O_3) Nitrogen dioxide (NO_2) Sulphur dioxide (SO_2) Carbon monoxide (CO)	AEA Technology (1 km grids, annual average concentrations, modelled from National Atmospheric Emissions Inventory (NAEI) data, 1999-2006)
Climate	Average temperature Cooling degree-days[1] Heating degree-days[2] Winter coldwave duration[3] Summer heatwave duration[4]	Meteorological Office UK Climate Impact Programme data (5 km grids, 1996-2003)
UV radiation	-	UVB Index (Mo and Green, 1974) calculated using Meteorological Office monthly cloud cover data (1 km grid, 1991-2000) and latitude
Industrial facilities	Waste management sites Metal production/processing sites	European Pollutant Emission Register (EPER) (grid references, 2001-2002)
Green space	-	Generalised Land Use Database (England only, 2001; Office of the Deputy Prime Minister, 2001) and Coordination of Information on the Environment Land Cover Data (CORINE data, UK, 2000; EEA, 2000)

[1] no. of degree-days above 22°c
[2] no. of degree-days below 15.5°c in winter months
[3] no. of days with daily minimum >3 °C below 1961-90 daily normal for ≥5 consecutive days (Nov-Apr)
[4] no. of days with daily maximum >3 °C above 1961-90 daily normal for ≥5 consecutive days (May-Oct)

Table 2. Sample calculation of the MEDIx score for two wards.

	Example 1: Kingston, Sussex (ward 21UFGL)		Example 2: Rotherhithe, Greater London (ward 00BEGT)	
In highest quintile for:	Yes/No	Score	Yes/No	Score
Detrimental dimensions:				
Air pollution?	No	0	Yes	+1
Proximity to industry?	Yes	+1	Yes	+1
Cold climate?	No	0	No	0
Beneficial dimensions:				
Green space?	Yes	-1	No	0
UVB?	Yes	-1	No	0
MEDIx score (= sum of scores)		-1		+2

Table 3. Characteristics of the MEDIx scores, including mean values (+ 95% CIs) of the environmental variables for each.

	MEDIx score					
	-2 (best)	-1	0	+1	+2	+3 (worst)
No. of wards	341	1,932	3,676	3,734	930	41
Population (2001)	922,001	7,266,436	16,654,053	26,444,631	7,254,766	249,980
Environmental dimension:						
Air pollutants						
SO_2 [a]	1.99 (1.89 - 2.09)	2.80 (2.75 - 2.84)	3.46 (3.40 - 3.52)	5.17 (5.09 - 5.26)	6.26 (6.09 - 6.43)	6.43 (5.90 - 6.97)
PM_{10} [a]	14.07 (13.94 - 14.20)	14.78 (14.72 - 14.84)	14.50 (14.43 - 14.56)	15.94 (15.87 - 16.02)	16.14 (16.00 - 16.28)	15.20 (14.78 - 15.61)
NO_2 [a]	13.91 (13.37 - 14.44)	18.14 (17.90 - 18.39)	19.29 (19.03 - 19.55)	26.43 (26.12 - 26.74)	26.97 (26.45 - 27.50)	25.47 (24.19 - 26.75)
CO [b]	0.15 (0.15 - 0.15)	0.17 (0.17 - 0.17)	0.19 (0.19 - 0.19)	0.25 (0.24 - 0.25)	0.25 (0.25 - 0.26)	0.24 (0.23 - 0.25)
Mean temperature (°C)	10.67 (10.63 - 10.71)	10.64 (10.62 - 10.66)	10.20 (10.18 - 10.23)	10.21 (10.18 - 10.24)	9.95 (9.89 - 10.00)	9.19 (9.10 - 9.28)
UVBI [c]	12.44 (12.41 - 12.46)	11.94 (11.90 - 11.97)	10.97 (10.94 - 11.01)	10.59 (10.55 - 10.62)	10.29 (10.23 - 10.36)	9.88 (9.63 - 10.13)
Industry [d]	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.02 (0.01 - 0.02)	0.05 (0.04 - 0.05)	0.32 (0.30 - 0.34)	0.53 (0.43 - 0.64)
Green space[e] (%)	94.08 (93.99 - 94.17)	77.53 (76.48 - 78.58)	68.28 (67.44 - 69.11)	49.79 (48.95 - 50.62)	49.62 (48.06 - 51.18)	53.27 (45.46 - 61.07)

[a] Mean of annual average (μg m^{-3}), 1999-2003
[b] Mean of annual average (mg m^{-3}), 2001-2006
[c] UVB Index (Mo and Green, 1974), unitless.
[d] % of ward's population living within 4 km of a waste management site or 1.6 km of a metal production or processing site
[e] % of the ward's area classed as 'green space'

Table 4. Characteristics of the MEDClass clusters, including mean values (+ 95% CIs) of the environmental variables for each.

	MEDClass cluster						
	1 London & London-esque	2 Industrial	3 Mediocre Green Sprawl	4 Fair-weather Conurbations	5 Cold, Cloudy Conurbations	6 Isolated, Cold and Green	7 Sunny, Clean and Green
No. of wards	840	673	1,955	1,649	988	1,691	2,858
Population (2001)	8,404,060	4,875,604	12,276,756	13,394,904	4,658,693	5,349,589	9,832,261
Environmental dimension:							
Air pollutants							
SO_2 [a]	4.77 (4.62 - 4.91)	5.40 (5.19 - 5.61)	4.95 (4.85 - 5.05)	5.28 (5.15 - 5.41)	4.84 (4.66 - 5.03)	2.77 (2.69 - 2.85)	3.05 (3.00 - 3.11)
PM_{10} [a]	18.73 (18.65 - 18.81)	16.27 (16.12 - 16.43)	16.01 (15.95 - 16.06)	16.59 (16.53 - 16.65)	13.90 (13.80 - 14.00)	12.31 (12.24 - 12.38)	14.67 (14.63 - 14.72)
NO_2 [a]	37.32 (36.91 - 37.73)	26.64 (26.05 - 27.24)	25.12 (24.87 - 25.36)	27.91 (27.65 - 28.17)	19.85 (19.39 - 20.31)	11.56 (11.28 - 11.84)	18.18 (17.98 - 18.38)
CO [b]	0.33 (0.32 - 0.33)	0.24 (0.24 - 0.24)	0.22 (0.21 - 0.22)	0.25 (0.25 - 0.26)	0.23 (0.22 - 0.23)	0.16 (0.16 - 0.16)	0.16 (0.16 - 0.16)
Climate							
WCWD[c]	4.54 (4.45 - 4.62)	3.78 (3.64 - 3.93)	4.10 (3.99 - 4.20)	4.03 (3.92 - 4.14)	3.45 (3.36 - 3.55)	3.45 (3.36 - 3.54)	4.38 (4.28 - 4.47)
SHWD[d]	15.14 (15.01 - 15.27)	13.45 (13.19 - 13.71)	13.67 (13.54 - 13.81)	13.22 (13.07 - 13.37)	7.59 (7.39 - 7.80)	9.25 (9.05 - 9.44)	13.48 (13.37 - 13.59)
CDD[e]	43.46 (43.09 - 43.82)	24.62 (23.72 - 25.51)	26.15 (25.70 - 26.61)	25.78 (25.36 - 26.21)	7.13 (6.91 - 7.35)	7.39 (7.19 - 7.58)	24.27 (23.87 - 24.66)
HDD[f] ('000)	1.81 (1.80 - 1.81)	2.09 (2.08 - 2.11)	2.06 (2.06 - 2.07)	2.04 (2.03 - 2.04)	2.32 (2.31 - 2.33)	2.43 (2.42 - 2.44)	2.07 (2.06 - 2.08)
UVBI [g]	11.97 (11.95 - 11.99)	10.98 (10.90 - 11.06)	11.44 (11.40 - 11.48)	11.32 (11.27 - 11.36)	9.32 (9.28 - 9.35)	9.57 (9.52 - 9.61)	11.65 (11.63 - 11.68)
Industry[h]	0.01 (0.01 - 0.01)	0.71 (0.69 - 0.72)	0.01 (0.01 - 0.01)	0.01 (0.01 - 0.01)	0.00 (0.00 - 0.01)	0.01 (0.00 - 0.01)	0.01 (0.01 - 0.01)
Green space [i] (%)	27.54 (26.50 - 28.59)	54.28 (52.41 - 56.16)	62.01 (61.46 - 62.56)	29.91 (29.44 - 30.38)	33.37 (32.61 - 34.12)	87.56 (87.09 - 88.02)	89.52 (89.30 - 89.75)

[a] Mean of annual average (μg m^{-3}), 1999-2003
[b] Mean of annual average (mg m^{-3}), 2001-2006
[c] Winter coldwave duration = no. of days with daily minimum >3 °C below 1961-90 daily normal for ≥5 consecutive days (Nov-Apr)
[d] Summer heatwave duration = no. of days with daily maximum >3 °C above 1961-90 daily normal for ≥5 consecutive days (May-Oct)
[e] Cooling degree-days = no. of degree-days above 22°c
[f] Heating degree-days = no. of degree-days below 15.5°c in winter months (given in thousands of degree-days)
[g] UVB Index (Mo and Green, 1974), unitless.
[h] % of ward's population living within 4 km of a waste management site or 1.6 km of a metal production or processing site
[i] % of the ward's area classed as 'green space'

Table 5. Cross-classification table, giving percentage of the UK population resident in each combination of MEDIx score and MEDClass cluster.

MEDClass cluster	MEDIx score					
	-2 (best)	-1	0	+1	+2	+3 (worst)
1 London & London-esque	0.00	0.02	2.75	10.87	0.66	0.00
2 Industrial	0.00	0.01	0.56	1.85	5.61	0.27
3 Mediocre Green Sprawl	0.00	3.26	7.61	8.19	1.72	0.10
4 Fair-weather Conurbations	0.00	1.91	5.32	13.71	1.84	0.01
5 Cold, Cloudy Conurbations	0.00	0.00	1.50	4.89	1.51	0.01
6 Isolated, Cold & Green	0.00	0.44	4.19	3.72	0.71	0.03
7 Sunny, Clean & Green	1.57	6.72	6.41	1.74	0.29	0.00

FIGURES

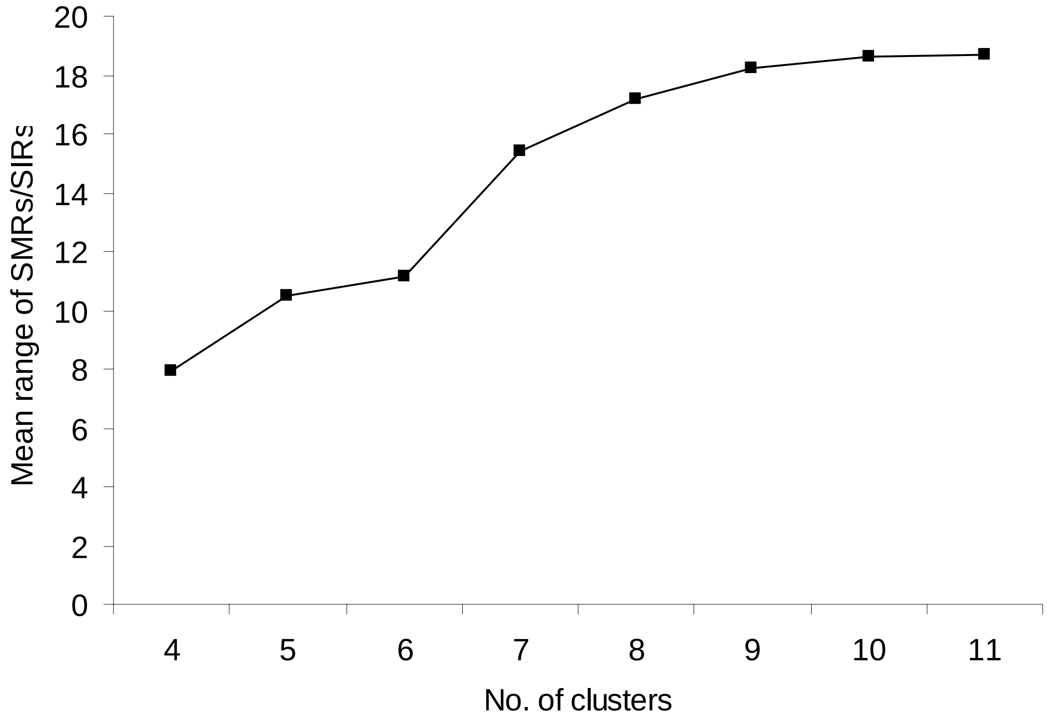

Figure 1. Plot of a solution's complexity (i.e., number of clusters) against its mean range of SMRs and SIRs. The marginal gain for additional complexity is reduced after the 7-cluster solution.

Figure 2. Distribution of MEDIx scores across UK CAS wards.

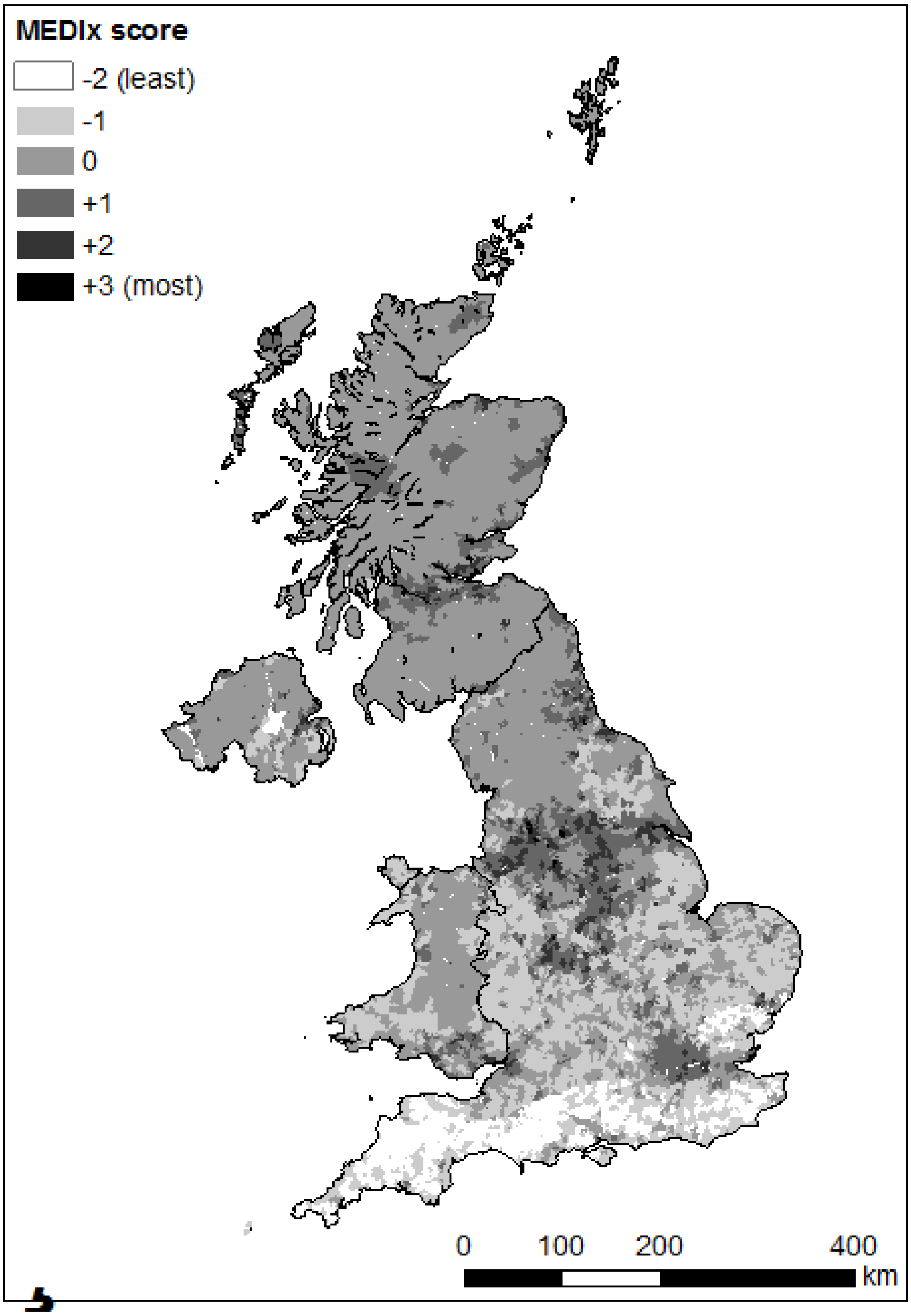

Figure 3 (Black&White). Distribution of MEDClass scores across UK CAS wards.

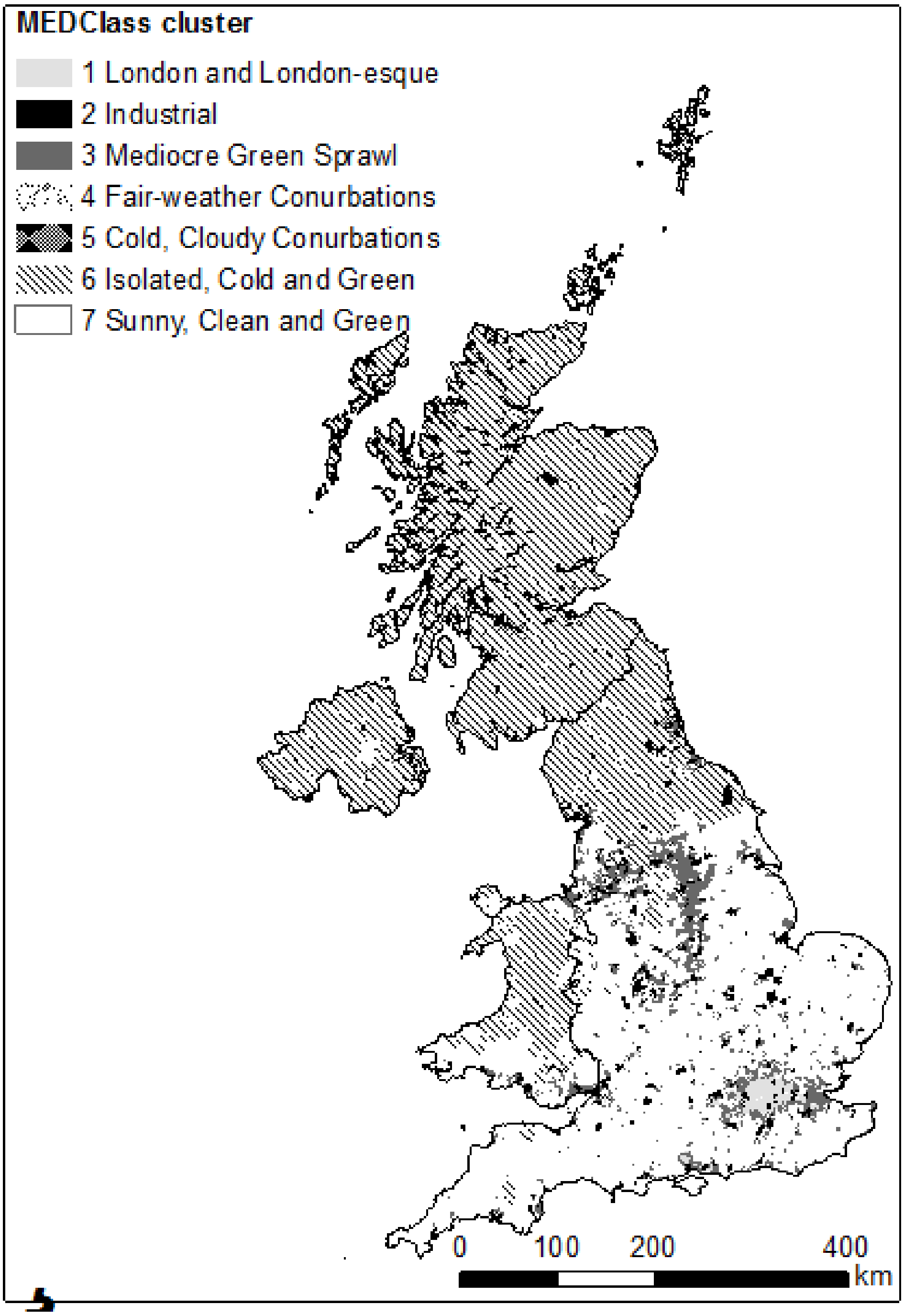

Figure 3 (Colour). Distribution of MEDClass scores across UK CAS wards.